MeV Dark Matter and Small Scale Structure

Dan Hooper[1], Manoj Kaplinghat[2], Louis E. Strigari[2] and Kathryn M. Zurek[3]
[1]*Theoretical Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[2]*Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697*
[3]*Phenomenology Institute, University of Wisconsin, Madison, WI 53706*

(Dated: February 1, 2008)

WIMPs with electroweak scale masses (neutralinos, etc.) remain in kinetic equilibrium with other particle species until temperatures approximately in the range of 10 MeV to 1 GeV, leading to the formation of dark matter substructure with masses as small as $10^{-4}\,M_\odot$ to $10^{-12}\,M_\odot$. However, if dark matter consists of particles with MeV scale masses, as motivated by the observation of 511 keV emission from the Galactic Bulge, such particles are naturally expected to remain in kinetic equilibrium with the cosmic neutrino background until considerably later times. This would lead to a strong suppression of small scale structure with masses below about $10^7\,M_\odot$ to $10^4\,M_\odot$. This cutoff scale has important implications for present and future searches for faint Local Group satellite galaxies and for the missing satellites problem.

PACS numbers: 95.35.+d;95.30.Cq; FERMILAB-PUB-07-064-A; MADPH-07-1482

Introduction. In the standard cosmology, featuring cold, collisionless dark matter, structures form hierarchically with the smallest mass objects forming first and progressively larger objects forming via subsequent mergers and accretion. This paradigm has been remarkably successful at describing the observed large scale structure.

Within this paradigm, the mass of the smallest dark matter halos depends on the mass of the dark matter particles, and on the temperature at which they decouple kinetically from other particle species. For a typical weakly interacting massive particle (WIMP) with an electroweak scale mass, kinetic decoupling from the standard model leptons occurs at a temperature in the range of roughly 10 MeV to 1 GeV, leading to the formation of structures with masses as small as $10^{-4}\,M_\odot$ to $10^{-12}\,M_\odot$ [1, 2]. If dark matter consists of particles which remain in kinetic equilibrium with neutrinos until later times (lower temperatures), the smallest dark matter halos will be considerably more massive than are predicted for WIMPs with electroweak scale masses [3].

Dark matter particles with MeV scale masses have been previously motivated by the observation of 511 keV emission from the Galactic Bulge [4, 5]. In particular, annihilating MeV dark matter can inject the required rate of positrons into the Galactic Bulge, and also be produced in the early universe with the measured dark matter abundance [5]. Dark matter in the form of MeV mass scalars, ϕ, annihilating through the exchange of a light gauge boson, U, can accommodate these requirements [5, 6, 7]. Constraints on this scenario have been placed by colliders [8, 9], neutrino experiments [10], atomic physics experiments [11], observations of supernova 1987A [12], the 511 keV line width [13] and Big Bang Nucleosynthesis (BBN) [14].

In this letter, we revisit the MeV dark matter scenario, and calculate the resulting matter power spectrum. We find that if the U-boson's couplings to neutrinos is similar to its couplings to electrons, the matter power spectrum is suppressed on small scales, leading to an absence of dark matter halos with masses below about $10^7\,M_\odot$ to $10^4\,M_\odot$. We show that this suppression scale is consistent with the region of parameter space where the MeV dark matter has the correct relic abundance as determined by recent cosmological observations [15].

The MeV Dark Matter Power Spectrum. To calculate the power spectrum for MeV dark matter, we start by determining the temperature at which kinetic decoupling occurs. The squared amplitude for dark matter-neutrino elastic scattering is given by

$$|\mathcal{M}_{\phi\nu}|^2 = \frac{8g^2_{U\phi\phi}g^2_{U\nu\nu}m^2_\phi E^2_\nu}{(t-m^2_U)^2}\Big[1+\cos\theta\Big], \qquad (1)$$

where $t=-2E^2_\nu(1-\cos\theta)$, m_ϕ is the mass of the dark matter particle, m_U is the mass of the exchanged boson, and $g_{U\phi\phi}$ and $g_{U\nu\nu}$ are that boson's couplings to dark matter and neutrinos, respectively. This leads to an elastic scattering cross section (in the $m_U \gg E_\nu$ limit) of

$$\sigma_{\phi\nu} = \frac{g^2_{U\phi\phi}g^2_{U\nu\nu}E^2_\nu}{2\pi m^4_U}. \qquad (2)$$

To determine the temperature of kinetic decoupling for the dark matter particle, we solve the Boltzmann equation, including the $\phi-\nu$ collision term. The resulting equation [16] is

$$\frac{df(\vec{p})}{dt} = \Gamma(T_\nu)(T_\nu m_\phi \nabla^2_{\vec{p}} + \vec{p}\cdot\nabla_{\vec{p}}+3)f(\vec{p})\,, \qquad (3)$$

where $\Gamma = 31\pi^3 g^2_{U\phi\phi}g^2_{U\nu\nu}T^6_\nu/(42m^4_U m_\phi)$ is the rate for the dark matter distribution function to relax to its equilibrium value. An intuitive approximation to this relaxation rate is $\dot{E}_k/E_k = (4\pi)^{-1}\int dE_\nu d\Omega(dn_\nu/dE_\nu)(d\sigma_{\phi\nu}/d\Omega)\delta E_k/E_k$ where dn_ν/dE_ν is the differential number density of all neutrinos, $E_k=|\vec{p}|^2/2m_\phi$ is the kinetic energy of dark matter particles and δE_k is the kinetic energy transferred per collision. This approximation yields $15.2g^2_{U\phi\phi}g^2_{U\nu\nu}T^6_\nu/(m^4_U m_\phi)$ for $E_k=3T_\nu/2$, which is a factor of about 1.5 smaller the exact result.

Eq. 3 is solved by a Boltzmann distribution with a temperature for the dark matter particle that scales as T_ν during the

strongly coupled regime and as T_ν^2 after decoupling. We define the kinetic decoupling temperature as $T_{\rm kd} = T_\nu$, such that $\Gamma(T_\nu) = H(T_\nu) \approx 5.97\sqrt{G_N}T_\nu^2$. This gives us

$$T_{\rm kd} = 2.1\,{\rm keV}\,\frac{m_U}{\rm MeV}\left(\frac{m_\phi}{\rm MeV}\right)^{1/4}\left(\frac{10^{-6}}{g_{U\phi\phi}g_{U\nu\nu}}\right)^{1/2}. \quad (4)$$

Using the formalism of Ref. [2], we can use this result to calculate the power spectrum of MeV dark matter.

The interactions and the subsequent decoupling of the dark matter particles leads to the damping of the matter power spectrum. This results from three distinct processes. First, the coupling of the dark matter to other particle species introduces damped oscillatory features [2]. This is the dominant effect for the case of WIMPs with electroweak scale masses. Second, after decoupling, the free-streaming of the dark matter particles further suppresses the power spectrum. For MeV dark matter, this effect dominates for the viable region of parameter space where $T_{\rm kd} \gtrsim {\rm keV}$. Third, as neutrinos kinetically decouple from the dark matter they begin to free-stream and damp the power spectrum further. This effect, however, is subdominant.

In Fig. 1, we show the effect on the matter power spectrum of MeV dark matter as compared to that for the standard cold dark matter case. Large wavenumbers are strongly suppressed, resulting in reduced number of small dark matter halos. Also shown in the figure as a dotted curve is the (strictest) limit found for the case of warm dark matter from observations of the lyman-alpha forest [17].

For $T_{\rm kd} \gtrsim {\rm keV}$, the scale at which the power spectrum is truncated is closely related to the free-streaming scale,

$$k_f^{-1} = 2.5\ {\rm kpc}\left(\frac{\rm keV}{T_{\rm kd}}\right)^{1/2}\left(\frac{\rm MeV}{m_\phi}\right)^{1/2}\ln(4a_{\rm EQ}/a_{\rm kd}), \quad (5)$$

where $a_{\rm kd}$ and $a_{\rm EQ}$ are the scale factors at decoupling and matter-radiation equality, respectively. The suppression of the dark matter power spectrum on scales smaller than k_f^{-1}, in turn, leads to a cutoff in the mass function of dark matter halos. Compared to the case with no cutoff, one would find a paucity of halos with masses less than roughly $4\pi(\pi/k_f)^3\,\rho_M/3$, where ρ_M is the present cosmological matter density. To obtain a more accurate estimate, we find the mass at which the expected number of dark matter halos falls by a factor of e compared to the prediction for dark matter particles with electroweak scale masses. We calculate the mass function of dark matter halos using the Press-Schechter prescription. We note that the validity of this prescription for power spectra with sharply truncated power (as found in our scenario) has not been conclusively demonstrated. Nevertheless, the cutoff mass derived here is useful in the sense that it highlights the mass scale below which we expect deviations from the predictions of standard cold dark matter. We find this cutoff mass to be

$$M_c \sim 3\times10^7 M_\odot\left(\frac{T_{\rm kd}}{\rm keV}\right)^{-3/2}\left(\frac{m_\phi}{\rm MeV}\right)^{-3/2}. \quad (6)$$

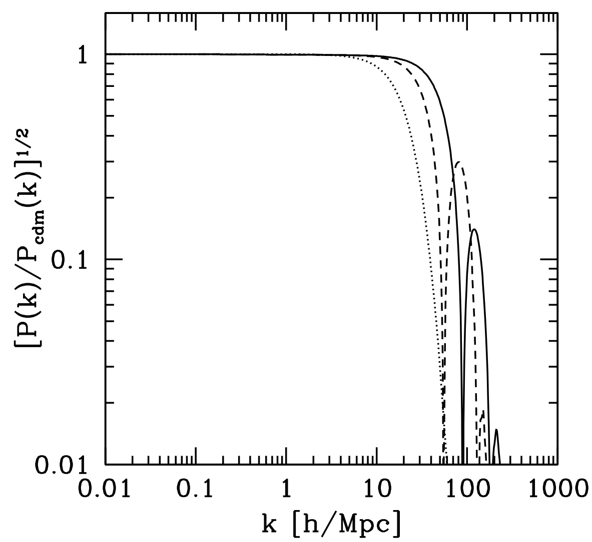

FIG. 1: The effect of keV scale kinetic decoupling on the matter power spectrum, as predicted in MeV dark matter. Shown are results for a 1 MeV dark matter particle with a 10 keV (solid) and 1.0 keV (dashed) kinetic decoupling temperature. The dotted line denotes the limit relevant for warm dark matter, as inferred from observations of the lyman-alpha forest [17].

Combining this expression with our specific particle physics scenario, we arrive at the estimate:

$$M_c \sim 10^7 M_\odot\left(\frac{m_U}{\rm MeV}\right)^{-3/2}\left(\frac{m_\phi}{\rm MeV}\right)^{-15/8}\left(\frac{g_{U\phi\phi}\,g_{U\nu\nu}}{10^{-6}}\right)^{3/4}. \quad (7)$$

We note that for $T_{\rm kd} \sim {\rm keV}$ and $m_\phi \sim {\rm MeV}$, the smallest halos that form (those with mass $\sim M_c$) are the ones that host the smallest of the dwarf galaxies seen in the Milky Way [18]. Therefore, the predictions for the number of Milky Way satellites will be different in this scenario compared to that for dark matter with electroweak scale masses. Numerical simulations with truncated power spectra that are able to resolve halos with masses below M_c and a detailed treatment of galaxy formation on small scales will be required to make robust predictions for the satellite (dwarf) galaxy population in galaxies like the Milky Way and Andromeda.

Relic Abundance and Other Constraints. There are a number of constraints on the various couplings and masses in MeV dark matter. First, we require that dark matter is thermally produced in the early universe with the observed abundance [15]. The annihilation cross section for scalar dark matter particles through the s-channel exchange of a U-boson is [6, 8]:

$$\begin{aligned}\sigma v \ &= \frac{g_{U\phi\phi}^2(s-4m_\phi^2)}{12\pi s[(s-m_U^2)^2+\Gamma_U^2 m_U^2]}\sum_f\sqrt{1-4m_f^2/s}\\ &\times\ [s(g_{f_L}^2+g_{f_R}^2)+m_f^2(6g_{f_L}g_{f_R}-(g_{f_L}^2+g_{f_R}^2))] \quad (8)\end{aligned}$$

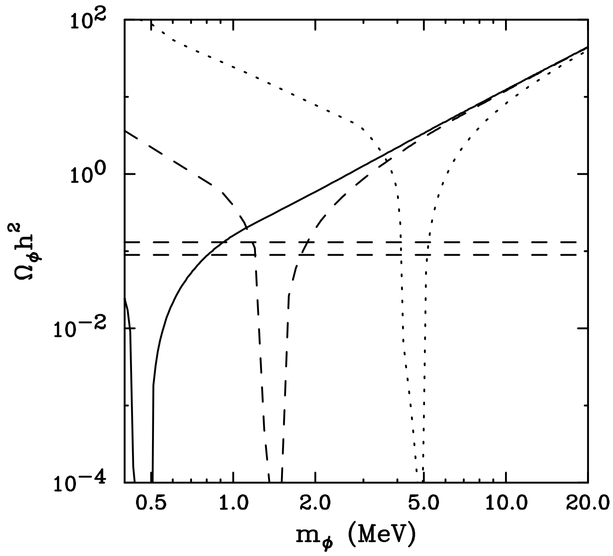

FIG. 2: The thermal relic abundance of dark matter as a function of its mass for $m_U = 1$ MeV (solid), 3 MeV (dashed) and 10 MeV (dotted). In each case, the product $g_{U\phi\phi} g_{Uff}$ was set to 10^{-6} for each of $f = e$, ν_e, ν_μ and ν_τ. The dashed horizontal lines denote the measured density of dark matter [15]. For illustration, we have shown the complete range for the dark matter mass, although only $m_\phi < m_U$ is viable [19].

where we have denoted the U couplings to left and right-handed fermions by g_{f_L} and g_{f_R}, respectively. The sum is over e^+e^- and the three species of neutrinos. Notice that at low velocities ($s \approx 4m_\phi^2$) the cross section approaches zero, being entirely the result of a P-wave amplitude.

In order for dark matter annihilations to generate the observed 511 keV photons from the Galactic Bulge, positrons must be injected with energies no greater than $\sim$ 3 MeV (more energetic positrons would unacceptably broaden the 511 keV line width). This leads to the constraint, $0.511\,\mathrm{MeV} \lesssim \mathrm{m}_\phi \lesssim$ 3 MeV [13]. We also require that $m_\phi < m_U$ in order to avoid dark matter annihilating largely to UU, which is not s-wave suppressed [19]. For a 0.511-3 MeV dark matter particle to be generated in a quantity consistent with the observed dark matter abundance, an annihilation cross section on the order of a picobarn is required during the freeze-out epoch.

We show in Fig. 2 the abundance of dark matter in this model as a function of its mass, for three values of the gauge boson mass, and for couplings of $g_{U\phi\phi} \times g_{Uff} = 10^{-6}$. Throughout, we adopt a common U-fermion-fermion coupling for electrons and neutrinos.

The U-boson's couplings to fermions are constrained by νe scattering experiments such that $g_{U\nu\nu}\sqrt{g^2_{Ue_Le_L} + g^2_{Ue_Re_R}} \lesssim m_U^2 G_F$ [6, 7]. For the case of a common U-fermion-fermion coupling, this reduces to $g_{Uff} \lesssim 2.9 \times 10^{-6} \times (m_U/\mathrm{MeV})^2$. A somewhat weaker constraint can be found from measurements of the electron's magnetic moment [6].

In Fig. 3, we show the range of m_U and the product $g_{U\phi\phi} \times g_{Uff}$ for which the measured dark matter density can be made to match the thermal relic abundance in this model (for some value of m_ϕ in the range of m_e to 3 MeV). We also show the constraints from νe scattering experiments (for the optimal case of $g_{U\phi\phi} \approx 1$) [6, 7] and from the measurement of the electron's magnetic moment [6].

As light blue lines, we have plotted contours of constant M_c from 10^7 to 10^4 solar masses. Here, we have used $m_\phi = 1$ MeV. For other masses, the results vary as $M_c \propto m_\phi^{-15/8}$. From this figure, we see that once all of the constraints are considered, M_c is generally expected to fall in the range of 10^4 to 10^7 $M_\odot$. It should be noted that the region where $m_U \approx 1-6$ MeV and $g_{U\phi\phi} g_{Uff} \lesssim 10^{-7}$ is highly fine tuned and relies on being very close to the resonance at $2m_\phi \simeq m_U$ to avoid the overproduction of dark matter.

The coupling of MeV dark matter to the neutrinos and electrons could change BBN predictions by causing the neutrino and photon temperatures to be the same to lower redshifts than is standard. Effects of this nature have been considered previously [14], though it is unclear how these constraints apply to this model on account of the presence of extra thermalized scalars and new neutrino interactions; a detailed analysis of the constraints from BBN is beyond the scope of this letter, but we have checked that there are viable regions of parameter space where the expected deviations from standard BBN predictions are within observational bounds [20].

MeV dark matter (and associated U-boson) with couplings to neutrinos would have other observable consequences. The existence of such a U-boson would lead to TeV scale absorption features in the high-energy cosmic neutrino spectrum [21]. The spectrum of neutrinos produced in core-collapse supernovae could also be modified due to their interactions with dark matter particles produced during the collapse [12].

Conclusions. In summary, we have calculated the small scale power spectrum of MeV dark matter. This scenario is motivated by the observation of 511 keV emission from the Galactic Bulge. Assuming that the relevant couplings to neutrinos are similar to those to electrons, we find that MeV dark matter particles remain in kinetic equilibrium with the cosmic neutrino background up to temperatures of $\sim$1-10 keV. This late kinetic decoupling leads to larger free-streaming lengths for MeV dark matter as compared to WIMPs with electroweak scale masses. This highly suppresses the formation of small scale structure. Depending on the parameters considered, the matter power spectrum is expected to be cutoff below 10^7 $M_\odot$ to 10^4 $M_\odot$ in this scenario.

This result has a number of particularly interesting astrophysical implications. First, it predicts a cutoff in the mass function of dwarf galaxies at a mass scale much larger than that for WIMPs with electroweak scale masses. It was previously shown that the number of dwarf galaxy-sized dark matter halos in numerical simulations of cold dark matter is considerably larger than the observed populations in the Milky Way and Andromeda galaxies (*ie.* the "missing satellites problem") [22, 23]. This issue may be resolved by astrophysical

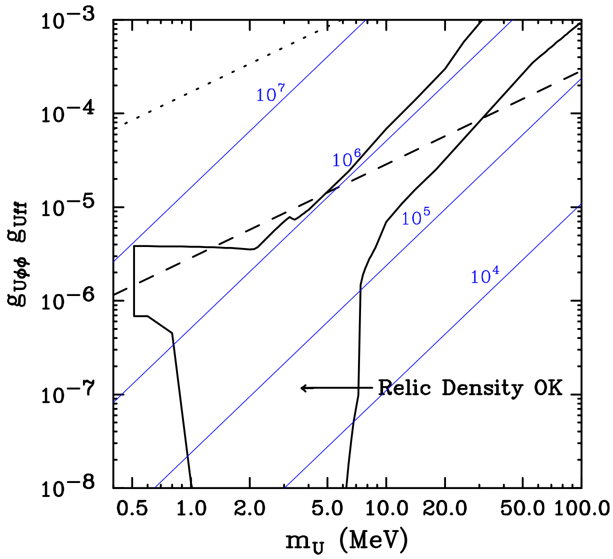

FIG. 3: Regions in the m_U versus $g_{U\phi\phi} g_{Uff}$ plane in which the measured dark matter density matches the thermal relic abundance for some value of m_ϕ in the range of m_e to 3 MeV. We have adopted a common U-fermion-fermion coupling for electrons and neutrinos. The dashed line denotes the constraint from νe scattering experiments (for the optimal case of $g_{U\phi\phi} \approx 1$) [6, 7]. The dotted line denotes the (weaker) constraint from measurements of the electron's magnetic moment [6]. The light blue lines are contours of constant M_c from 10^4 to 10^7 solar masses. Here, we have used $m_\phi = 1$ MeV. From this figure, we see that once all of the constraints are considered, M_c in the range of 10^4 $M_\odot$ to 10^7 $M_\odot$ are generally expected.

means [24] or by altering the nature of the dark matter's interactions [25] or mechanism of production [26]. The model we consider falls into this latter category, though detailed numerical simulations will be required to make precise predictions of the satellite population in MeV dark matter.

Tests of dark matter models with observations of small scale structure, as we have discussed in this paper, are becoming a more realistic possibility given the recent discoveries of faint satellite companions to the Milky Way and Andromeda galaxies [27]. Present estimates of the masses of these new satellites fall in the range 10^5 $M_\odot$ to 10^7 $M_\odot$, which is near the cutoff mass scale in MeV dark matter. Present and future searches for faint satellites, and the characterization of the mass function at these scales, will thus provide important constraints on MeV dark matter.

We thank John Beacom for discussions on this topic. This work has been supported by the US Department of Energy, including grant DE-FG02-95ER40896, and by NASA grant NAG5-10842, and by NSF grants AST-0607746 and PHY-0555689. We acknowledge the Aspen center for Physics where this work was initiated.

[1] X. l. Chen, M. Kamionkowski and X. Zhang, Phys. Rev. D **64**, 021302 (2001). V. Berezinsky, V. Dokuchaev and Y. Eroshenko, Phys. Rev. D **68**, 103003 (2003); A. M. Green, S. Hofmann and D. J. Schwarz, Mon. Not. Roy. Astron. Soc. **353**, L23 (2004); JCAP **0508**, 003 (2005); S. Profumo, K. Sigurdson and M. Kamionkowski, Phys. Rev. Lett. **97**, 031301 (2006);
[2] A. Loeb and M. Zaldarriaga, Phys. Rev. D **71**, 103520 (2005).
[3] G. Mangano, *et al.*, Phys. Rev. D **74**, 043517 (2006); C. Boehm, *et al.*, arXiv:astro-ph/0309652.
[4] P. Jean *et al.*, Astron. Astrophys. **407**, L55 (2003).
[5] C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, Phys. Rev. Lett. **92**, 101301 (2004).
[6] C. Boehm and P. Fayet, Nucl. Phys. B **683**, 219 (2004).
[7] P. Fayet, Phys. Rev. D **70**, 023514 (2004).
[8] N. Borodatchenkova, D. Choudhury and M. Drees, Phys. Rev. Lett. **96**, 141802 (2006).
[9] B. McElrath, Phys. Rev. D **72**, 103508 (2005); P. Fayet, arXiv:hep-ph/0607094; M. Ablikim *et al.* [BES Collaboration], Phys. Rev. Lett. **97**, 202002 (2006); P. Fayet, Phys. Rev. D **74**, 054034 (2006).
[10] C. Boehm, Phys. Rev. D **70**, 055007 (2004).
[11] C. Bouchiat and P. Fayet, Phys. Lett. B **608**, 87 (2005).
[12] P. Fayet, D. Hooper and G. Sigl, Phys. Rev. Lett. **96**, 211302 (2006).
[13] J. F. Beacom and H. Yuksel, Phys. Rev. Lett. **97**, 071102 (2006); J. F. Beacom, N. F. Bell and G. Bertone, Phys. Rev. Lett. **94**, 171301 (2005).
[14] E. W. Kolb, M. S. Turner and T. P. Walker, Phys. Rev. D **34**, 2197 (1986); P. D. Serpico and G. G. Raffelt, Phys. Rev. D **70**, 043526 (2004);
[15] D. N. Spergel *et al.* [WMAP Collaboration], arXiv:astro-ph/0603449.
[16] E. Bertschinger, Phys. Rev. D **74**, 063509 (2006); T. Bringmann and S. Hofmann, arXiv:hep-ph/0612238.
[17] U. Seljak, *et al.*, Phys. Rev. Lett. **97**, 191303 (2006); M. Viel, *et al.*, Phys. Rev. Lett. **97**, 071301 (2006).
[18] L. E. Strigari, S. M. Koushiappas, J. S. Bullock and M. Kaplinghat, arXiv:astro-ph/0611925.
[19] C. Jacoby and S. Nussinov, arXiv:hep-ph/0703014.
[20] R. H. Cyburt, B. D. Fields, K. A. Olive and E. Skillman, Astropart. Phys. **23**, 313 (2005) [arXiv:astro-ph/0408033].
[21] D. Hooper, arXiv:hep-ph/0701194; S. Palomares-Ruiz and T. Weiler, in progress.
[22] A. A. Klypin, *et al.*, Astrophys. J. **522**, 82 (1999).
[23] B. Moore, *et al.*, Astrophys. J. **524**, L19 (1999).
[24] J. S. Bullock, A. V. Kravtsov and D. H. Weinberg, Astrophys. J. **539**, 517 (2000); A. V. Kravtsov, O. Y. Gnedin and A. A. Klypin, Astrophys. J. **609**, 482 (2004); B. Moore, *et al.*, Mon. Not. Roy. Astron. Soc. **368**, 563 (2006).
[25] C. Boehm, P. Fayet and R. Schaeffer, Phys. Lett. B **518**, 8 (2001); X. l. Chen, S. Hannestad and R. J. Scherrer, Phys. Rev. D **65**, 123515 (2002).
[26] K. Sigurdson and M. Kamionkowski, Phys. Rev. Lett. **92**, 171302 (2004); J. A. R. Cembranos, *et al.*, Phys. Rev. Lett. **95**, 181301 (2005); M. Kaplinghat, Phys. Rev. D **72**, 063510 (2005).
[27] B. Willman *et al.*, Astrophys. J. **626**, L85 (2005); D. B. Zucker *et al.* [SDSS Collaboration], Astrophys. J. **643**, L103 (2006); V. Belokurov *et al.* [SDSS Collaboration], Astrophys. J. **654**, 897 (2007).